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Codetection of acoustic emissions during failure of heterogeneous media: New perspectives for natural hazard early warning

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Key Points:
- A method for detecting imminent failure using elastic wave emissions is proposed
- It harnesses heterogeneity and attenuation of natural media for event detection
- The method capitalizes on event codetection as surrogate for large failures

Correspondence to:
J. Faillettaz,
jerome.faillettaz@geo.uzh.ch

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Codetection of acoustic emissions during failure of heterogeneous media: New perspectives for natural hazard early warning

Jerome Faillettaz[1], Dani Or[2], and Ingrid Reiweger[3]

[1]3G, Department of Geography, University of Zürich, Zürich, Switzerland, [2]Soil and Terrestrial Environmental Physics, ETHZ, Zürich, Switzerland, [3]Institute for Snow and Avalanche Research (SLF), WSL, Davos, Switzerland

Abstract A simple method for real-time early warning of gravity-driven rupture that considers both the heterogeneity of natural media and characteristics of acoustic emissions attenuation is proposed. The method capitalizes on codetection of elastic waves emanating from microcracks by multiple and spatially separated sensors. Event codetection is considered as surrogate for large event size with more frequent codetected events marking imminence of catastrophic failure. Using a spatially explicit fiber bundle numerical model with spatially correlated mechanical strength and two load redistribution rules, we constructed a range of mechanical failure scenarios and associated failure events (mapped into acoustic emission) in space and time. Analysis considering hypothetical arrays of sensors and consideration of signal attenuation demonstrate the potential of the codetection principles even for insensitive sensors to provide early warning for imminent global failure.

1. Introduction

Gravity-driven instabilities in natural earth materials including rockfalls, landslides, snow avalanches, or glacier break offs represent an important class of natural hazards in mountainous regions. Reliable prediction of imminence of such failure events combined with timely evacuation remains a challenge due to the nonlinear nature of geological material failure hampered by inherent heterogeneity, unknown initial mechanical state, and complex load application (rainfall, temperature, etc.) that hinder predictability. Nevertheless, such materials exhibit certain characteristics during failure; they break gradually with the weakest parts breaking first, during which they produce precursory "microcracks" and associated elastic waves traveling in the material. The monitoring of such acoustic/microseismic activity offers valuable information concerning the progression of damage and imminence of global failure [*Michlmayr et al.*, 2012]. Acoustic emission methods are advancing rapidly and are expected to provide new insights into the imminence of instabilities, and in some cases it has been applied to natural gravity-driven instabilities such as cliff collapse [*Amitrano et al.*, 2005], slope instabilities [*Dixon et al.*, 2003; *Kolesnikov et al.*, 2003; *Dixon and Spriggs*, 2007], or failure in snowpack [*Van Herwijnen and Schweizer*, 2011; *Reiweger et al.*, 2015].

An important technical challenge hindering application of such early warning methods is the attenuation of elastic waves propagating through the natural media, thereby introducing ambiguity in the interpretation of the magnitude (severity) or leading to loss of detection for events away from the sensor. Hence, a microcrack event would be measured as a large event if occurring close to the sensor and as a small event if far from the sensor (or may not be detected at all). A more complete picture of acoustic emissions or microseismic activity requires deployment of a dense network of sensors that enables localization of sources and thus the determination of initial energy released with each event. Unlike reservoir and other short-term targeted applications, we seek a method that capitalizes on sparse and infrequent information for a process that is extremely rapid when it occurs. We thus require minimum computational needs, low cost, and functional detection threshold to permit simple and robust applications. Is it possible to directly analyze in real time the measured microseismic activity to infer the slope mechanical status? The objective of this work is to propose a simple method focusing on event codetection for identifying large failure events and use of their frequent occurrence as precursors for imminent failure.

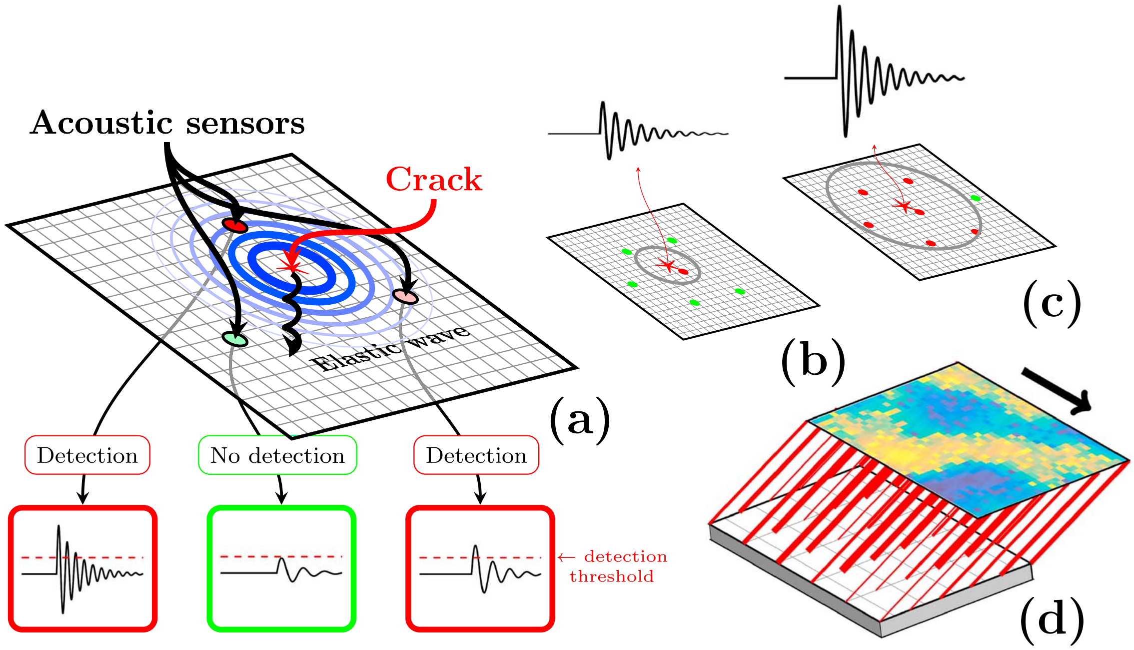

Figure 1. (a) Schematic view of the attenuation problem. Star indicates the initial crack location and blue circles the resulting elastic wave that propagates through the medium. Schematic waveforms recorded at the different sensors are also represented. Schematic illustration of codetection method with sensor network for (b) a small event and (c) a large event: Star indicates microcrack location with its associated waveform on top, and colored disks indicate sensor location. Grey circles represent distance of detection of the event knowing detection threshold of sensors. Dark red disks show the sensors that detected the signal and light green the sensors that do not detect the event. The larger the event, the higher the number of sensors that detect the event concurrently. (d) Schematic view of the 2-D spatially explicit fiber bundle model as analogous to a natural slope. Width of red lines indicates fiber strength, also represented on the top (from weak dark blue to strong light yellow).

The paper is organized as follows: We first provide a qualitative description of the observation problem and the processes leading to attenuation. Taking advantage of both the heterogeneity of natural media and the attenuation phenomenon, a new method based on codetection properties is introduced. A quantitative analysis is then performed using a numerical model based on the classical fiber bundle model (FBM). Introducing a basic attenuation law in such simple models enables to directly compare unattenuated and attenuated acoustic activity (and also avalanche size frequency distribution) at any location. After investigating the effects of attenuation phenomena on possible stability assessment, the codetection method is examined. Finally, the potential application of this method to early warning purposes are discussed.

2. Qualitative Approach: The Observation Problem

2.1. Effects of Elastic Wave Attenuation

Natural slopes act as a low-pass filter. Acoustic waves propagating in natural media attenuate due to geometrical reduction in elastic energy density with distance from the source (geometric spreading); e.g., the energy of spherical wavefront emanating from a point source is distributed over a spherical surface of ever increasing size. Since energy is proportional to amplitude squared, an inverse square law for energy translates to a $1/r$ decay law for amplitude.

Additionally, changes in material properties and heterogeneities give rise to signal scattering, excitation of other modes of wave propagation, and inelastic absorption (that dissipates elastic energy to heat). The resulting acoustic emission (AE) signal amplitude decay and dispersive effects are enhanced in the presence of pore water and air-water interfaces (especially in the presence of pore water) [*Oelze et al.*, 2002; *Wang and Santamarina*, 2007; *Müller et al.*, 2010]. Consequently, attenuation phenomena are enhanced in wet materials close to rainfall-induced failure. Inelastic attenuation and scattering effects are frequency dependent, and higher frequencies of the waveform attenuate preferentially. Due to attenuation of propagating acoustic signals (elastic waves), an event (i.e., a crack in the material) may be observed and recorded differently by an acoustic sensor depending on its location (Figure 1).

In general, acoustic sensors detect a signal if the wavefront amplitude exceeds a detection threshold (Figure 1). Thus, the detection range for a given sensor location depends on both the sensor detection threshold and on AE signal initial amplitude. Additionally, an event is detected if the "signal-to-noise ratio" (SNR) is sufficiently large to distinguish it from background noise. The only requirement for the detection threshold is thus to set it higher than the SNR to ensure meaningful detection. Depending on the studied natural instability, the environmental conditions, and the available sensors, such minimum detection threshold can evolve without affecting the outcome (see section 3.3.3).

Attenuation phenomenon introduces ambiguity into the interpretation of the signal amplitude (distance and attenuation mask signal size). This dependency plays an important role in the resulting amplitude-frequency distribution derived from sensor measurements, since exchanges of amplitude from the real to the attenuated — i.e., the recorded — signal are possible. Assessing imminence of a catastrophic failure with amplitude-frequency distribution of the recorded signal [e.g., *Amitrano et al.*, 2005] becomes invariably biased.

2.2. Harnessing the Attenuation Phenomenon: Signal Codetection

The attenuated wave amplitude may fall below a sensor detection threshold. Considering a small-amplitude event, attenuation dictates that such an event will be detected only if it occurs close to a sensor (Figure 1b). In contrast, for large initial amplitude, the same event could be detected by more than one sensor in the network (Figure 1c).

Hence, event codetection by multiple sensors occurs only if its initial amplitude of the event is sufficiently large. Naturally, codetection would also depend on the sensor network geometry and detection threshold. Nevertheless, for any practical sensor network, signal codetection offers a simple means for directly assessing the likelihood of a large-amplitude event in real time (without the need of postprocessing recorded signals). A simple on/off trigger (detection or no detection) combined with an accurate time synchronization (to ensure that the same event is detected on several sensors) would thus be sufficient to infer the minimum amplitude of the source as well as an approximate location of the source (depending on the location of the sensors in the network that detect the same event). Quality and type of sensors would thus be less important than often required for other applications.

Unlike most applications and methods to study and detect Earth-related processes, heterogeneity does not mask or hinder the detection. On the contrary, when codetection is observed in a heterogeneous system, the fidelity and significance of the event are even enhanced. Moreover, heterogeneity acts as a filter that injects randomness and perturbs traveltimes, priming thus the role of codetection (events that transcend this "heterogeneity filter" are considered significant).

3. A Quantitative Approach

3.1. Model Description

To quantitatively evaluate the effect of attenuation phenomenon on the detection of precursory acoustic activity and propose methodology for early warning system based on the codetection method, a numerical model was used to systematically evaluate the potential of such an approach. Several models for heterogeneous material failure and fracturing exist in the literature (see *Sornette* [2006], *Alava et al.* [2006], and *Bonamy and Bouchaud* [2011] for a review). We selected the FBM for its simplicity and generality as a useful framework for systematically studying processes preceding global failure *Pierce* [1926]; *Daniels* [1945]; *Gómez et al.* [1993]; *Kloster et al.* [1997]; *Alava et al.* [2006]; *Pradhan et al.* [2010]; *Faillettaz and Or* [2015]. In essence, the model represents natural heterogeneous materials as a set of elastobrittle fibers that are mechanically loaded in parallel (Figure 1d); each fiber deforms in a linear elastic manner and breaks instantly at its prescribed rupture strength (whose values are drawn from a prescribed probability distribution). The load carried by the failed fiber is then redistributed according to specific rule ranging from global load sharing on all the surviving fibers (called DFBM) to local load sharing on their neighboring fibers (called LFBM), which could give rise to cascading failure events ("avalanches"). The FBM framework provides a simple and mechanically consistent means to study precursory signals preceding catastrophic rupture using recorded signals only. Additionally, the discrete nature of failure events offers a direct link with acoustic emissions suggested for monitoring such progressive failures *Michlmayr et al.* [2012]. The application of 2-D spatially explicit FBM-based models (Figure 1d) has already provided new insights especially in terms of early warning perspectives. Recent developments [*Faillettaz and Or*, 2015] highlighted the important roles of spatial correlation of mechanical properties and load redistribution rules on failure statistics and global failure of the FBM. The failure mode for the spatially explicit FBM varies dramatically with increasing spatial correlation length of mechanical properties and localized load sharing rules. Systems with similar composition of mechanical elements exhibit a dramatic transition from ductile and diffuse damage for global load sharing (DFBM) to brittle single failure for correlated and local load sharing (LFBM). These changes in mechanical responses also affect the statistical properties of fiber failure avalanche (microcracks) activity preceding rupture and sought after in various early warning scenarios [*Amitrano*, 2012].

Whereas diffuse damage behavior exhibits clear precursory signals (such as increased seismic activity prior to global failure), brittle failure occurs abruptly with only few precursors [*Faillettaz and Or*, 2015]. Although increasing spatial correlations of mechanical properties promote abrupt ruptures at lower external load, a "universal" global failure criterion based on macroscopic properties was obtained. This criterion is independent of the rupture mode, stress redistribution rules, or the spatial organization of mechanical properties.

However, the study of *Faillettaz and Or* [2015] did not account for attenuation phenomena and the useful results in terms of early warning perspective might be biased under natural conditions where the signal recorded by a sensor at a given location has been attenuated. We thus aim to use this FBM as a tool to investigate the impact of attenuation on the existence of precursory signs of impeding rupture, especially signs linked to the statistical properties of the avalanche size frequency distribution prior to global failure.

3.2. Spatial FBM With Attenuation—Model Development

We introduced signal attenuation effects into the spatial FBM developed by *Faillettaz and Or* [2015]. Attenuated amplitudes are computed (i) assuming that they are proportional to the initial "failure avalanche" size (i.e., the number n of failed fibers at each load increment) and (ii) accounting for geometrical spreading effects only (the divergence of elastic energy density with radial distance from the source). In this simplified representation, we ignore several important interactions such as intrinsic and scattering attenuation that depend on material properties and frequency content and thus are difficult to quantify, in contrast with geometrical decay that occurs always. Knowing both the location of a sensor X_{sensor} and each single fiber failure X_{ff} during the computed failure avalanche, the attenuated amplitude A_a is simply evaluated by summing the individual attenuated amplitudes of each individual fiber failure reaching the sensor, i.e.,

$$A_{\mathrm{a}} = \sum_{\mathrm{ff}=1}^{n} \frac{A_0}{\|X_{\mathrm{ff}} - X_{\mathrm{sensor}}\|} \tag{1}$$

where A_{a} is the attenuated amplitude reaching the sensor and A_0 the initial amplitude caused by a single fiber failure. It is thus possible to access the statistical distribution of the attenuated avalanche sizes and their evolution prior to global failure.

3.3. Results

3.3.1. Size Frequency Distributions for Attenuated Elastic Signal

Notwithstanding its simplicity, the model supports systematic evaluation of the effects of attenuation on the recorded statistical behavior of microcrack activity prior to rupture for different rupture mechanisms, i.e., brittle-like to ductile-like rupture. *Faillettaz and Or* [2015] have shown that load redistribution rules play a major role in the rupture behavior ranging from brittle-like rupture for local load redistribution (LFBM) to ductile-like behavior for global load redistributions (DFBM). Figure 2 shows a comparison between avalanche size frequency distribution (SFD) deduced from FBM failure events for the original (unattenuated) and attenuated events (taking $A_0 = 1$ in equation (1) to permit comparison of the results) computed at different random location of sensors. Results indicate that the exact location of a sensor has no effect on the size frequency distribution of attenuated avalanches (Figure 2), irrespective of the nature of global rupture behavior, i.e., brittle like (LFBM) or ductile like (DFBM). Statistical distribution of attenuated avalanche size remains indeed similar from one sensor location to another. This unintuitive result is of practical interest as one would expect that sensor location would directly influence the recorded signal and thus affect predictive capabilities.

Moreover, differences in SFD characteristics appear when comparing original and attenuated simulations, especially in LFBM (Figure 2b), i.e., when considering local load redistributions. In this case, contrary to DFBM where the system is invariant by translation (because of uniform load redistribution and periodic boundary conditions), LFBM still exhibits power law avalanche size distribution but with significantly lower b exponent (exponent characterizing the power law exponent, i.e., $P(s) \sim s^{-b}$) in the attenuated case. This suggests that the proportion of small recorded avalanches (group of fiber failures) decreases in SFD deduced considering attenuation. The modification of the recorded statistical behavior (when accounting for attenuation)

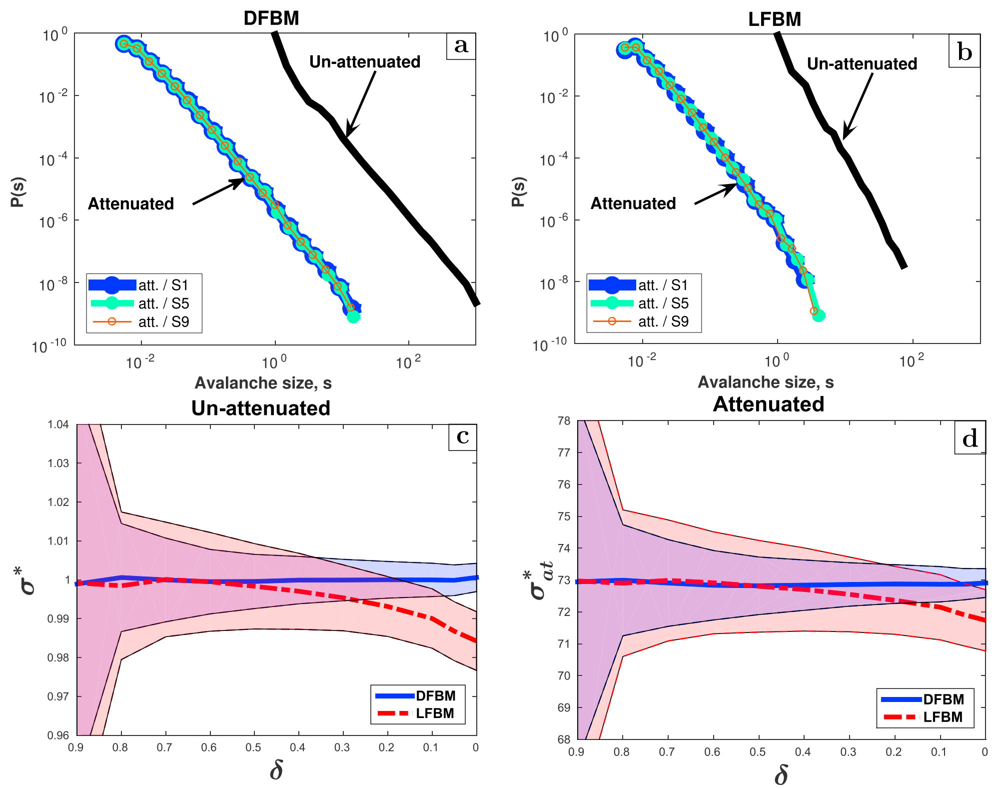

Figure 2. (a and b) Avalanche size distribution deduced from original (unattenuated) model results (black line) and considering attenuation at three different random locations (color symbols) for DFBM (Figure 2a) and LFBM (Figure 2b). (c and d) Evolution of the global failure criterion developed by *Faillettaz and Or* [2015] (see text for detail) as the system approaches failure (along the coordinate $\delta = \frac{\sigma_c - \sigma}{\sigma_c}$ where σ_c marks the stress at the critical failure state) for original unattenuated results (Figure 2a) and considering effects of attenuation (Figure 2b). The color hatched area around the full (DFBM) and dashed (LFBM) lines are 95% confidence interval constructed by 200 Monte Carlo simulations.

relative to the original behavior suggests that this piece of information only might not be appropriate for early warning purposes.

3.3.2. Signal Evolution Toward Global Failure

In order to characterize how fiber failure event size distribution evolves toward the macrofailure, we computed SFD for successive bins of the control parameter δ. As the simulations were realized under stress-controlled conditions, $\delta = \frac{\sigma_c - \sigma}{\sigma_c}$, σ_c marking the stress at the critical point. δ represents also the relative stress toward failure (with a value of $\delta = 0$ marking failure). To ensure reliable statistical representation, we stacked 200 simulations for each configurations (DFBM and LFBM) taking a total number of fibers equal to 256×256.

Figure 2c (lower left corner) shows the evolution toward rupture of a mechanical metric termed the "damage-weighted stress" $\sigma^\star$ proposed by *Faillettaz and Or* [2015] that accounts for damage accumulation and expressed as $\sigma^\star = \frac{\sigma^{\mathrm{tot}}}{E\,(1-D)D}$ where σ^{tot} is the total stress applied on the bundle and D the associated damage defined as the ration between cumulative number of avalanches (i.e., the total number of failed fibers) and the total number of fibers in the bundle. This damage-weighted stress appears to be constant close to 1 for DFBM and slightly decreasing for LFBM when approaching global failure as noted by *Faillettaz and Or* [2015]. Additionally, we define damage in the presence of attenuation as the ratio between the cumulative attenuated avalanche size and the total number of fibers, i.e., an "attenuated damage-weighted stress" σ^*_{at}. Results show that evolution of both damage metrics approaches global rupture in a very similar way (Figure 2d). This suggests that although different, the analysis of attenuated signals provides useful information on the imminence of global rupture.

Figure 3 depicts the evolution of size frequency distribution of original (unattenuated) and attenuated avalanche size close to global failure of DFBM and LFBM: The SFD appears to change just prior to global failure, and the simulated b exponent decreases as the system approaches catastrophic rupture in agreement with

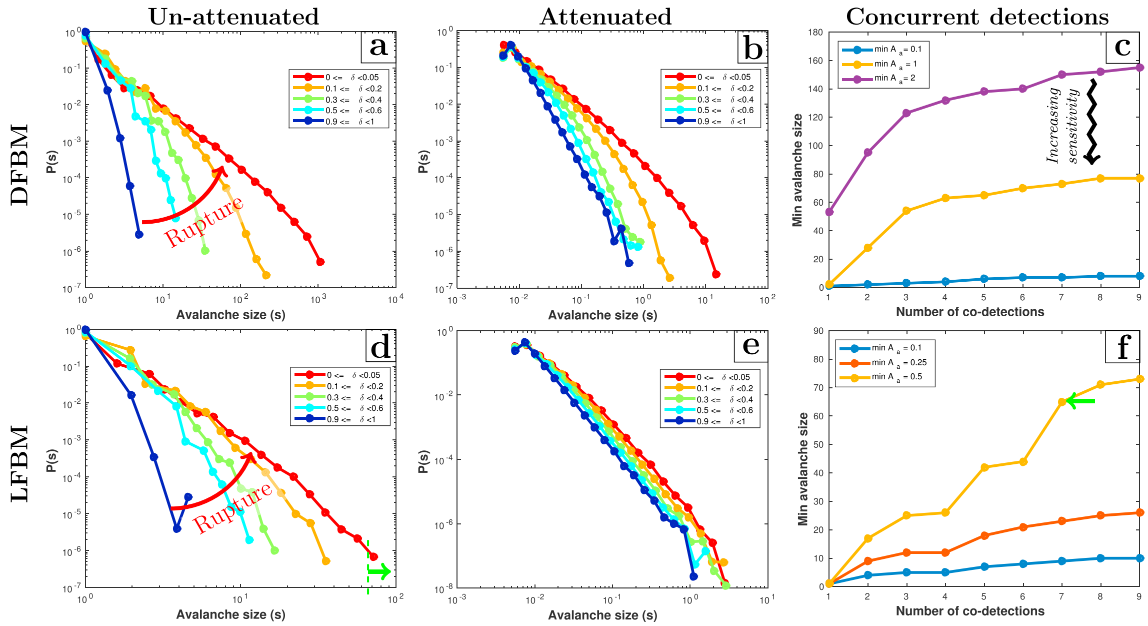

Figure 3. Evolution of size frequency distribution when approaching rupture for (a and d) original (unattenuated) and (b and e) attenuated avalanches in DFBM (Figures 3a and 3b) and LFBM (Figures 3d and 3e). (c and f) The minimum original (unattenuated) avalanche size as a function of the number of sensors concurrently detecting the same event for different detection thresholds (i.e., minimum A_a has been detected) for DFBM (Figure 3c) and LFBM (Figure 3f): For example, in LFBM, if an event is codetected by seven sensors with a threshold of 0.5 (green arrow in Figure 3f), the minimum avalanche size of the corresponding unattenuated event would be 70 indicating an imminent failure of the bundle ($\delta < 0.05$, green arrow in Figure 3d).

analytical results for ductile-like rupture (DFBM) [*Pradhan et al.*, 2005]. Decreasing *b* exponent prior to rupture was suggested to constitute a useful tool for assessing the mechanical state of a failure-sensitive slope of geological structure [*Pradhan et al.*, 2005; *Amitrano*, 2012]. Such effect is, however, not recovered very clearly when considering attenuated amplitudes (Figures 3b and 3e), especially in the case of brittle-like rupture (LFBM), making this property less useful for early warning purpose in practical real cases (with attenuation). On the other hand, the ability to detect the occurrence of large (unattenuated) events would provide valuable information on the proximity of rupture as the larger events only occur near the global rupture and would thus provide a way to assess slope stability at proximity to rupture.

3.3.3. Codetection as a Component of Early Warning

The FBM model was used to evaluate the simple theoretical method based on codetection proposed in section 2.2. As shown in Figure 3a or 3b, the minimum initial amplitude of the microcrack generated in the failing earth material or slope (represented by the spatial FBM) could be assessed by investigating both the number of sensors codetecting an event and by tuning sensor detection threshold. The larger the number of concurrent detections (codetection events), the larger the initial amplitude of the local failure event. Interestingly, higher sensor threshold values select for codetection of larger initial amplitude event. Figure 3 shows that taking a sufficiently large threshold and number of codetection events, the minimum size of the unattenuated events would fall in the range of $0 < \delta < 0.1$, i.e., just prior to rupture. For example, in the LFBM, if an event is codetected by seven sensors with a threshold of 0.5 (yellow line, green arrow in Figure 3f), the minimum size of the unattenuated event would be 70 (interpreted as 70 fibers failing at once) indicating an imminent failure of the bundle ($\delta < 0.05$, green arrow in Figure 3d).

These results suggest that the codetection method could provide a simple and cost-effective way of detecting the occurrence of very large events that announce impeding global rupture, provided that sensor detection threshold is correctly tuned. In practice, such detection thresholds could be tuned by posterior analysis introducing a flexible way to investigate the large event. Codetection method would thus constitute a simple, flexible, and efficient way to assess imminence of rupture in real time without processing a large amount of data.

A perquisite for the implementation of the codetection method is the capability to accurately synchronize time stamps among sensors in the network. The parameters for such time synchronization would vary with the

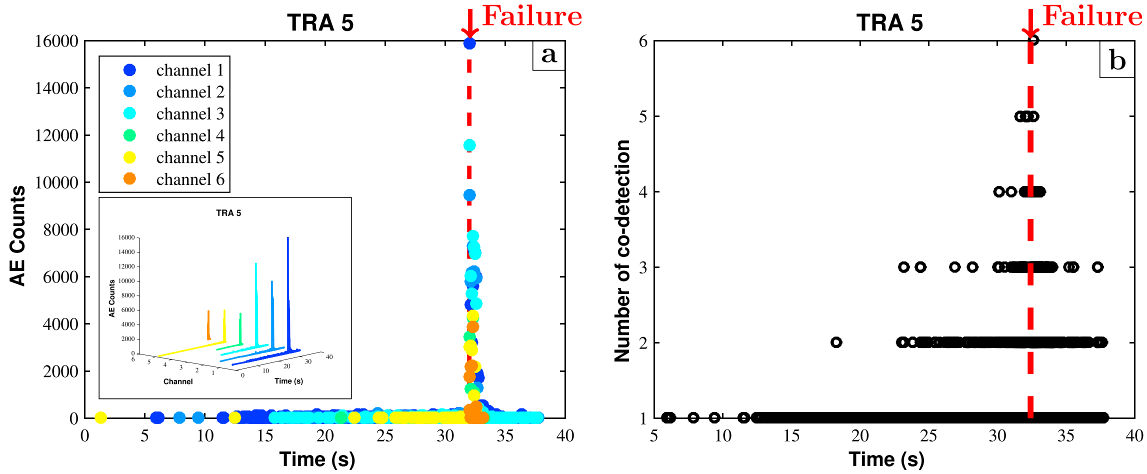

Figure 4. Experimental data of recorded acoustic emission (AE) activity during a force-controlled loading of layered snow sample [*Reiweger et al.*, 2015]. (a) Global recorded acoustic emission (AE) counts from the six channels (experiment "TRA 5"); each event has been represented as a colored dot, and inset shows the separated trace of each channel for the same data. (b) Number of sensors detecting concurrently the same event. Red dashed line marks the failure of the snow sample.

material properties and the network geometry. For example, to detect the same event concurrently in rock, the time synchronization should be better than a millisecond, taking 3 m as the minimum distance between two sensors in the network and an average elastic wave speed of 3000 m s^{-1} in rock [*Hamilton*, 1978].

Note that the codetection method is general and should hold for any waves propagating in any material considering homogeneous attenuation properties. However, we do not address in this study neither intrinsic attenuation nor scattering effects (that highly depend on frequency content of the wave). Both effects further enhance attenuation phenomenon, leading to drastic attenuation especially at high frequency. The codetection method remains valid as long as the attenuated wave is detectable, i.e., amplitude higher than the background noise. In practice, the geometry of the sensor network has to be adapted to the studied frequency domain: The higher the frequency range, the smaller the distance between sensors in the network. In several field tests it was found that damping of acoustic signals requires a dense network of acoustic emission sensors leading to strong practical limitations [*Dixon et al.*, 2015]. New emergent techniques such as distributed fiber-optic acoustic emission acquisition could also significantly extend the effective coverage with the ability to detect elastic waves continuously along the optical cable. Alternatively, signals at lower frequencies could offer observability advantage provided they are linked to precursory mechanical failure events. Subjected to less attenuation, such waves can be detectable at a larger distance, with seismic sensors or accelerometers.

4. Application

To test the applicability of the proposed codetection method, we used cold laboratory experiments that recorded acoustic emissions activity generated during a force-controlled loading of layered snow samples containing a weak layer [*Reiweger et al.*, 2015]. The acoustic measurement system consisted of wideband piezoelectric AE transducers (20–1000 kHz), preamplifiers (with 40 dB gain), band-pass filters, digitizers, a personal computer, and the recording and analysis software AEwin [*Reiweger et al.*, 2015]. The threshold was set to 28 dB. The analysis of the acoustic data revealed a decrease of the *b* exponent of the complementary cumulative distribution of event energy during the catastrophic failure, as evidenced by the "numerical" behavior depicted in section 3.3.2 and Figure 3. Six acoustic sensors located in the snow sample were recording concurrently the acoustic activity prior to the catastrophic failure, enabling thus the codetection method to be tested. We show here results for loading experiment on sample TRA 5 as such small sample experienced a clear catastrophic failure with a clear drop in *b* exponent prior to failure [*Reiweger et al.*, 2015].

This illustrative application shows a sudden increase in signal maximal amplitude (AE counts) less than 1 s prior to sample failure (Figure 4a); however, the increase in codetection of AE event started approximately 10 s earlier (culminating in all six sensors codetecting the large event occurring at failure, Figure 4b). This simple example illustrates the robustness of codetection as a potentially useful metric for real-time early warning without detailed amplitude analysis (resulting in further computational efforts). It is yet unclear how much lead time is gained, in general, by the codetection method (an order of magnitude in the simple example above); however, we expected the value to depend on the nature of the failure event (ductile versus brittle) and other localization considerations. In practice, further work is needed to apply such method at larger scale (i.e., slope scale): As higher frequency are more attenuated (due to inelastic absorption), reducing frequency band for codetection (to the kHz range or even lower) might be required for real applications to large-scale instability.

5. Summary and Conclusions

Early warning systems are often based on the monitoring of the temporal evolution of external parameters such as geometry, surface displacements, or meteorological variable (e.g., rainfall duration and intensity). Our study proposes a method based on continuous monitoring and interpretation of acoustic emissions and their characteristics as surrogates of mechanical states of the system (hillslope, glacier, and snow cover). The method capitalizes on both heterogeneity and attenuation properties of natural media to develop a new strategy for early warning systems. The study introduces a heuristic and simple method based on codetection of elastic waves traveling through natural media. It requires a network of (seismic/acoustic) sensors on a potential unstable slope and monitor events detection in real time. Real-time processing of measured events that are detected concurrently on more than one sensor (codetected) would then enable to easily access their initial size as well as their initial location. Such method provides a simple means to access characteristics and temporal evolution of surrogate variables linked to hillslope damage and mechanical state. Simple numerical model based on FBM accounting for geometric attenuation confirms the early warning potential of codetection. Results suggest that although statistical properties of attenuated signal amplitude could lead to misleading results, monitoring the emergence of large events announcing impeding failure is possible even with attenuated signals depending on sensor network geometry and detection threshold. In this context, the sensors must not be very sensitive (i.e., a low threshold is not needed) to assess slope stability but the network needs to be precisely synchronized: Temporal synchronization between sensors must be sufficient to reliably classify events detected concurrently by multiple sensors. Preliminary application of the proposed method to acoustic emissions during failure of snow samples has confirmed the potential usefulness of codetection as indicator for imminent failure. More tests are needed to refine aspects of threshold codetection and their statistical properties for real early warning systems.

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